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New satellite mission with old data: Rescuing a unique data set

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[1] We review efforts to save a unique data set and scientific results based on the rescued data. The goal of the project was to produce Alouette 2, ISIS 1, and ISIS 2 digital topside ionograms from selected original seven-track analog telemetry tapes. This project was initiated to preserve a significant portion of 60 satellite years of analog data, collected between 1962 and 1990, in digital form before the tapes were discarded. More than 1/2 million digital topside ionograms are now available for downloading at http://nssdcftp.gsfc.nasa.gov and for browsing and plotting at http://cdaweb.gsfc.nasa.gov. We illustrate data products, discuss analysis programs, review scientific results based on the digital data, and recognize those who made the project possible. The scientific results include evidence of extremely low altitude ionospheric peak densities at high latitudes, improved and new ionospheric models including one connecting the F2 topside ionosphere and the plasmasphere, transionospheric HF propagation investigations, and new interpretations of sounder-stimulated plasma emissions that have challenged theorists for decades. The homepage for the ISIS project is at http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html.

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1. Introduction

[2] The International Satellites for Ionospheric Studies (ISIS) program included four Canadian built and U.S. launched polar-orbiting satellites: Alouette 1 and 2, and ISIS 1 and 2 launched in 1962, 1965, 1969 and 1971, respectively. Alouette is the French term for Lark. The two Alouette satellites were each in operation for 10 years; ISIS 1 was in operation for 21 years and ISIS 2 for 19 years. Each contained ionospheric topside sounders designed as analog systems with the data recorded on magnetic tapes at a network of more than 20 globally distributed telemetry stations as illustrated in Figure 1. Not all of the sounder data recorded on these tapes were converted into 35-mm film ionograms because of cost considerations. In addition, only about 177,000 of the millions of Alouette 1 and 2 and ISIS 1 and 2 35-mm film ionograms were processed into topside vertical electron density profiles $N_e(h)$ because of the manual effort involved. In 1996, approximately 100,000 original Alouette 1, Alouette 2, ISIS 1 and ISIS 2 seven-track analog telemetry tapes remained in storage under the control of the Communications Research Centre (CRC) in Canada. More than 80% of these were from ISIS 1 and ISIS 2. Space limitations and storage costs, however, threatened the long-term survival of these data. The NASA Ionosphere, Thermosphere, Mesosphere (ITM) Data Evaluation Panel, noting the importance of these multisolar-cycle observations of the topside ionosphere and the danger of loosing these data, gave highest priority to an Alouette/ISIS data restoration project. A project was initiated to produce digital ionograms directly from a large number of the Alouette 2 and ISIS 1 and 2 original seven-track analog telemetry tapes [*Benson*, 1996]. The tapes selected for analog-to-digital (A/D) conversion provided good latitudinal and seasonal coverage across the mission time period (see Figure 1 and *Benson* [1996] and *Bilitza et al.* [2004]). Approximately 16,200 telemetry tapes from these satellites were shipped to the NASA Goddard Space Flight Center (GSFC) for A/D conversion (13,800 in March 1996 and 2,400 in July 2006), 2,500 remain at CRC in Canada for possible later A/D conversion at GSFC, and (unfortunately) 81,000 went to a Canadian landfill. Of those shipped to GSFC, approximately 15,700 have been processed

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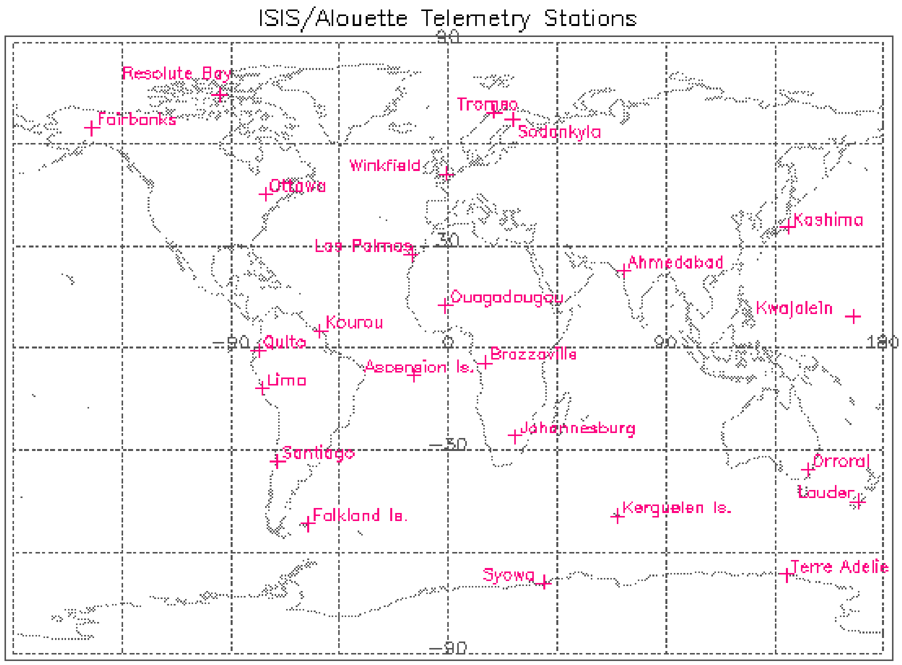

Figure 1. Global distribution of Alouette/ISIS telemetry stations used in the data rescue project. The station names and coordinates are given by *Benson* [1996] and *Bilitza et al.* [2004].

with support from the ITM Data Panel, the NASA Applied Information Systems Research (AISR) and Living With a Star Targeted Research and Technology (LWS TR&T) programs, and internal GSFC support. More than 1/2 million digital ionospheric topside ionograms are now available on line from the National Space Science Data Center (NSSDC) at ftp://nssdcftp.gsfc.nasa.gov. A large number of the ISIS 2 digital ionograms have been automatically processed to produce $N_e(h)$ profiles using the Topside Ionogram Scaler With True Height Algorithm (TOPIST) software specifically developed for this purpose [*Huang et al.*, 2002; *Bilitza et al.*, 2004]. The TOPIST $N_e(h)$ profiles also present a comparison between values for the F2 layer peak plasma frequency foF2, and the altitude of this peak hmF2, as determined by TOPIST from the ionospheric reflection traces and as obtained from International Reference Ionosphere (IRI) [*Bilitza*, 2001] model predictions. These profiles, in addition to the $N_e(h)$ profiles from earlier hand scaling efforts, are available from the above NSSDC ftp site. Figure 2 presents histograms of the distributions of the digital ionograms and the $N_e(h)$ profiles available from each satellite by year.

[3] When the Very Low Frequency (VLF) receiver (rather than the sounder) was operational, the VLF signal was digitized and placed on 4-mm Digital Audio Tapes (DAT) for deposition in the NSSDC. The ISIS 1 and ISIS 2 Pulse Code Modulation (PCM) data were also preserved and are available on line from the NSSDC as are header files containing orbital, instrument mode, and A/D information for each digital ionogram. The former can be used (with some difficulty) to determine the orientation of the satellite and the antenna phase at a particular time during the recording of an ionogram. The latter provides a useful compliment to the ionogram CDAWeb display capability. For more information about the project, see the ISIS project homepage at http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html.

[4] One of the first truly international and long-lasting satellite projects, the ISIS program excited not only the scientific community but also the broader public as documented by many international postage stamps (see Figure 3). After nearly 50 satellite years of support, ISIS operations were terminated by the CRC in Canada on 9 March 1984; ISIS operations resumed in early August 1984 under the control of the Radio Research Laboratories in Japan and continued until 24 January 1990 [*Jackson*, 1986; H. G. James, personal communication, 1990]. The ISIS program also included two U.S. built satellites, namely, Explorer 20 (launched on 25 August 1964) and Explorer 31 (launched piggyback with Alouette 2 on 29 November 1965; this combined launch was known as ISIS X). Explorer 20 contained a fixed-frequency ionospheric topside sounder capable of oper-

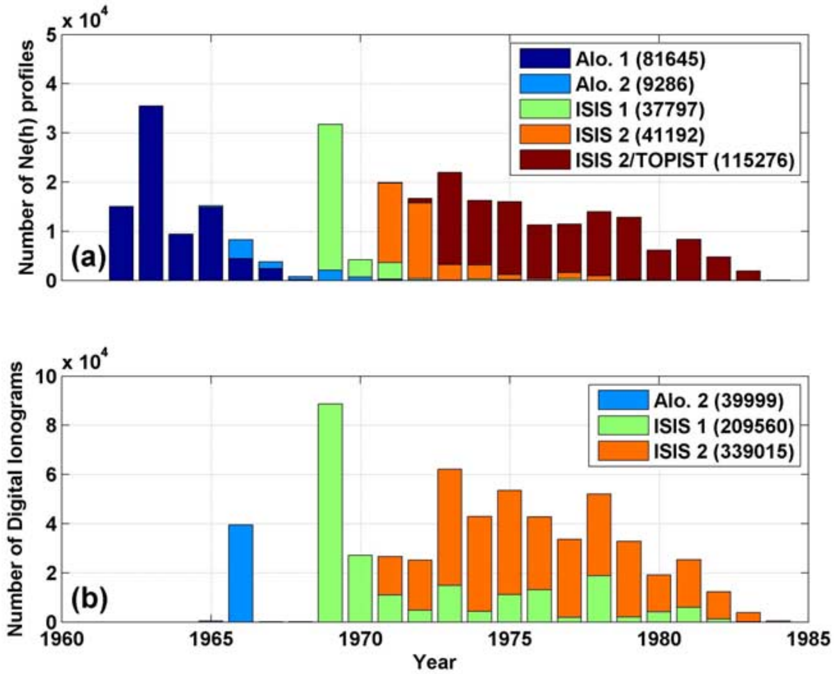

Figure 2. Data sets available from the NSSDC as of 30 January 2009: (a) Manually scaled topside $N_e(h)$ profiles from Alouette 1 and 2 and ISIS 1 and 2 35-mm film topside ionograms and automatically (TOPIST) scaled ISIS 2 profiles from digital ionograms and (b) digital topside ionograms from Alouette 2, ISIS 1, and ISIS 2 selected for global coverage and to complement the earlier manually scaled data (note the factor of 2 change in scale relative to Figure 2a). They are distributed among more than 20 globally distributed telemetry stations and were selected to (1) obtain global coverage over more than a solar cycle, (2) complement existing $N_e(h)$ profiles based on earlier manual scaling of Alouette/ISIS topside ionograms in the analog 35-mm film format, and (3) address subjects and time periods of special interest as specified by H. G. James, R. F. Benson, J. D. Craven, and R. T. Tsunoda. Many of the ISIS 2 digital ionograms have been automatically processed by H. K. Hills using the TOPIST software of X. Huang [*Bilitza et al.*, 2004; *Huang et al.*, 2002].

Figure 3. International postage stamps commemorating the Alouette/ISIS program.

ating on six logarithmically spaced frequencies. This mode of operation, which was extremely valuable for the study of ionospheric N_e gradients and plasma resonances, was incorporated into the normal operating modes of ISIS 1 and ISIS 2. Explorer 31, also known as Direct-Measurements Explorer A (DMEA), allowed for comparisons among several in situ measurement techniques against the nearby sounder that was used as the standard [*Donley et al.*, 1969]. Here we emphasize the new Alouette 2 and ISIS 1and ISIS 2 digital ionograms; a review of additional international topside sounder programs has been given by *Pulinets and Benson* [1999].

[5] Sample topside sounder data products are presented in section 2, analysis tools are discussed in section 3, scientific results are reviewed in section 4 followed by acknowledgments to the large number of individuals who made it possible to preserve and analyze these data in a digital format.

2. Sample Alouette 2, ISIS 1, and ISIS 2 Digital Topside Ionograms

[6] The digital topside ionograms were produced directly from the original seven-track analog telemetry tapes rather than by the much less accurate process of scanning and digitizing ionograms from the large inventory of 35-mm film. In most cases the digital ionograms correspond to times when 35-mm film ionograms do not exist (hence the title of the paper: New satellite mission with old data ...). We start our discussion with ISIS 2 because data from ISIS 2 were the first to be digitized at GSFC with the goal of producing a global distribution of topside ionospheric $N_e(h)$ profiles over more than a solar cycle from this polar-orbiting satellite in a nearly circular orbit near 1400 km altitude. Next, examples from ISIS 1 and Alouette 2, in polar elliptical orbits of 550×3500 km and 500×3000 km, respectively, will be presented.

[7] The primary instrument on each of the four Alouette/ISIS satellites was an ionospheric radio sounder designed to probe the ionosphere from the altitude of the satellite down to the altitude h_{max} of the ionospheric peak N_e, i.e., the topside of the ionosphere. These topside sounders were similar in that they all were designed as analog instruments that radiated high power (100 to 400 W), short duration ($\sim$0.1 ms) radio frequency pulses from one of two crossed spin-plane dipoles of different lengths and signals were received, using the same dipole as for transmission, for a time interval (tens of milliseconds) sufficient to receive long-range ionospheric echoes (down to h_{max}). Each sounder incorporated improvements based on experience gained from its predecessors [*Franklin and Maclean*, 1969; *Benson*, 1972].

[8] The sounders on ISIS 1 and ISIS 2 were the most similar in that they each used 400 W pulses, 18.8 and 73.2 m tip-to-tip BeCu crossed dipoles (the short dipole on Alouette 2 was 22.9 m), had similar automatic-gain-control (AGC) time constants, and had several modes of operation. Three modes are most commonly found in the data. The first is a combined fixed- and swept-frequency mode. About 3.3 s of operation at a fixed frequency is followed by a quasi-logarithmic sweep from 0.1 to 10 (normal sweep) or 20 MHz (extended sweep). The second is the D mode where every two normal ionograms are followed by two with the sounder transmitter off. It enables natural emissions to be distinguished from sounder-induced signal returns from the ambient plasma. The third is the G mode where normal ionograms (as in the first mode) are interleaved with ionograms where the transmitter and receiver remain at a fixed frequency. This mode is extremely valuable in the investigation of plasma gradients along the satellite trajectory, the physics of short-range electrostatic echoes and sounder-stimulated plasma emissions, and in identifying signal modulations caused by the satellite spin. For more information, see *Florida* [1969] for the satellites and *Franklin and Maclean* [1969] and *Daniels* [1971] for the sounders.

[9] Figure 4 presents an ISIS 2 ionogram operating in the first mode described above with an extended frequency sweep to 20 MHz. It is displayed using one of the analysis tools, which offers a variety of color and black and white viewing options, to be described in the next section. The apparent range of the left-hand scale corresponds to $ct/2$ where c is the vacuum speed of light and t is the round-trip delay time on the right-hand scale. The X, O, and Z ionospheric reflection traces, correspond to the extraordinary and ordinary fast modes and the slow branch of the X mode, respectively, and stalactite-like short-duration signals (termed plasma resonances) clinging to the top of the ionogram, are clearly visible. None of these features are labeled in order to illustrate how the data appear when first displayed. These features are identified on later ionograms in this paper and in the work of *Hagg et al.* [1969].

[10] The fixed-frequency sounding at 1.95 MHz on the left side of Figure 4 illustrates the effect of antenna spin modulation on the combined O and X traces near 1000 km apparent range (where the traces fade near the end of the 3.3 s fixed-frequency sounding interval) and on a plasma resonance feature that is observed with an extended time duration only for a short time near the beginning of the fixed-frequency interval. The slight inflection of the ionospheric reflection traces at 2.0 MHz is caused by a change in the frequency sweep rate at 2.0 MHz (there is another sweep-rate change at 5.0 MHz). It is the frequency region just prior to this 2.0 MHz marker, where the two ionospheric reflection traces merge, that is being sampled by the fixed frequency sounding. The gap in the reflection

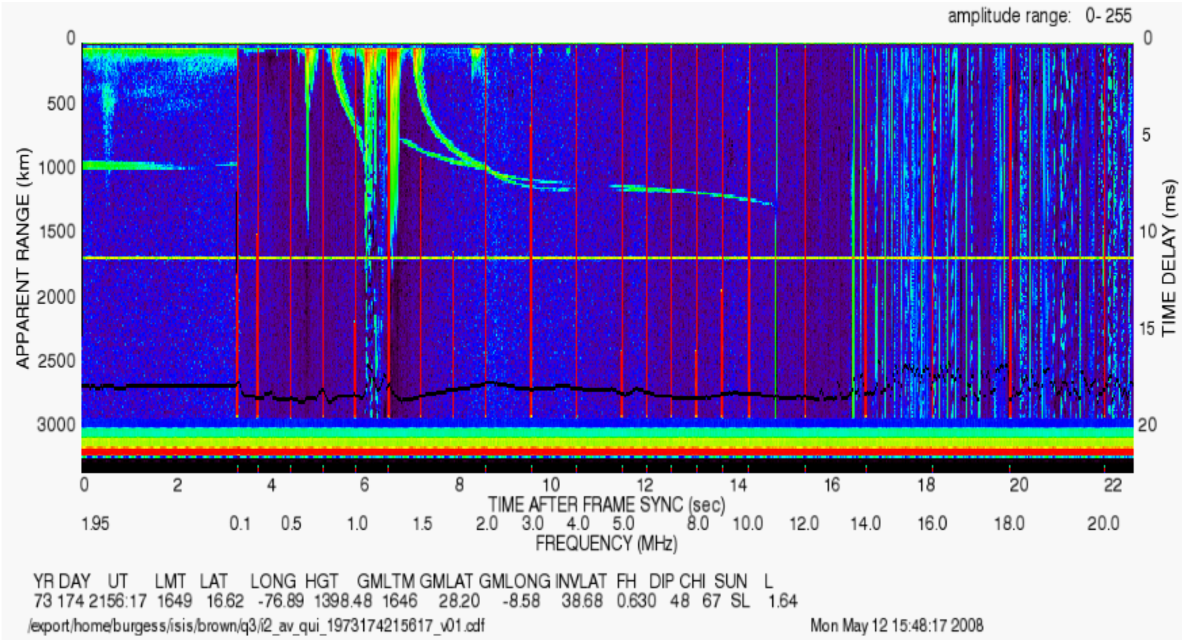

Figure 4. ISIS 2 Quito (QUI) digital topside fixed/swept-frequency ionogram (year 1973, day 174, 2156:17 UT) displayed using analysis software available from http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html. It displays the amplitude-modulated sounder-receiver video amplitude (strongest signal is red in the color viewing option or black in the black and white option) versus the time delay after the sounder pulse (right scale) expressed as apparent range (left scale) and time after the ionogram start time (frame sync) and sounder frequency (top and bottom of the two bottom scales, respectively). The vertical lines (starting at 0.1 MHz) are frequency markers (which are superimposed on the receiver video output), the horizontal line near the middle of the ionogram is a calibration range marker (11.11 ms time delay, 1667 km apparent range), and the wavy line between 2500 and 3000 km apparent range indicates the AGC voltage. World map information, the file name, and the date of the image production are provided below the frequency scale. No amplitude thresholding was used in this case, i.e., all 256 amplitude levels per 15 km apparent range step were used as indicated in the top right. See the text and the ISIS homepage given above for more details.

traces in the 4–5 MHz frequency interval is caused by the crossover from the long dipole used for the lower frequencies to the short dipole used for higher frequencies (the crossover frequency is 5.0 MHz for ISIS 1 and 2 and 4.6 MHz for Alouette 2) [*Franklin and Maclean*, 1969].

[11] Among the most challenging tasks in the A/D operation was the detection of the frame-sync pulse (designating the start of an ionogram) and the frequency markers within an ionogram. The ionogram in Figure 4 represents an example where all of these identifications were made properly. There are 22 frequency markers on the ionograms from each of the satellites processed. On ISIS 1 and 2 they occur at 0.1, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 3.0 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 12.0, 14.0, 16.0, 18.0, and 20.0 MHz on extended-sweep ionograms such as shown in Figure 4. The identification of these markers by the A/D software is indicated by the tick marks below the ionogram (the marks at 1.50 and 1.75 MHz do not appear on this reproduction but are present in the original data). On normal-sweep ionograms (up to 10 MHz), only 17 markers are present. The 22 frequency markers on Alouette 2 appear at 0.1, 0.2, 0.5, 0.55, 0.9, 1.25, 1.5, 1.6, 2.0, 2.5, 3.5, 4.5, 5.5, 6.5, 7.0, 7.5, 8.5, 9.5, 10.5, 11.5, 12.5, and 13.5 MHz but the one at 0.1 MHz is not a calibrated frequency marker (it designates the start of the frequency sweep) and is referred to as a pseudomarker [*Hagg et al.*, 1969]. Most of the Alouette 2 ionograms were recorded with the frequency markers on a separate track rather than being imbedded in the sounder-receiver video signal as on the ISIS ionograms. Once the frequency markers were iden-

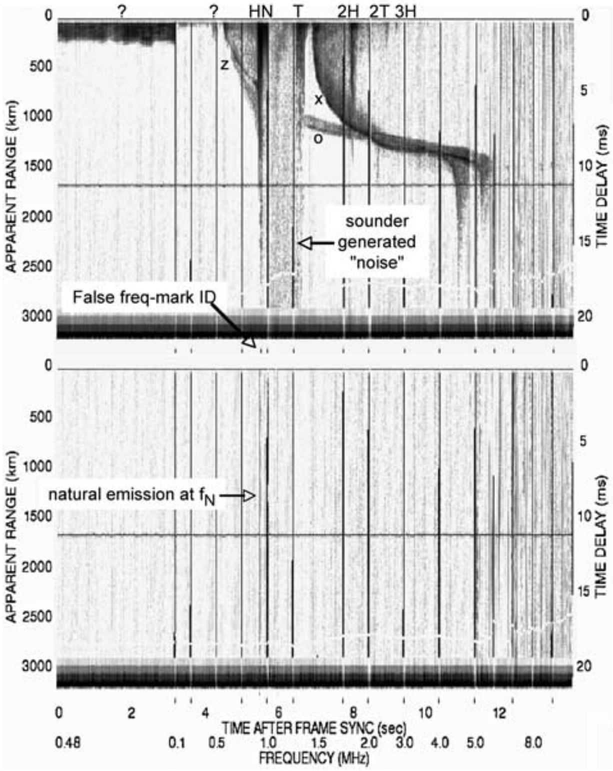

Figure 5. Same as Figure 4 except consecutive ISIS 2 Resolute Bay (RES) (year 1971, day 231) digital topside fixed/swept-frequency ionograms with 0.48 MHz fixed frequency and normal 0.1–10.0 MHz sweeps and operating in the D mode. (top) Transmitter on (0146:17 UT). (bottom) Transmitter off (0146:31 UT). Plasma resonances at the electron plasma frequency f_N, the electron gyrofrequency f_H, f_H harmonics, the upper hybrid frequency f_T, and at $2f_T$ are identified as N, H, the numbers 1–7, T, and 2T, respectively, where $f_T^2 = f_N^2 + f_H^2$; the plasma resonance identified by question marks on both fixed and swept frequency is not understood; it is possibly due to nonlinear processes (it may correspond to 2H-T), e.g., see *Benson* [1982] for a description of such resonances.

tified, and tagged with the appropriate times, an interpolation was performed to determine the frequency to associate with each sounder scan-line time. A different process was used on ISIS 1 and Alouette 2, than on ISIS 2, to increase the number of ionograms with useable frequency interpolation. Also, a special frequency interpolation process was used on ISIS 1in order to be consistent with a GSFC analysis program's technique for compensating for large frequency sweep nonlinearities in portions of the ionogram. See Appendix A and the ISIS homepage for more details.

[12] Figure 5 (top) illustrates an ISIS 2 ionogram where a false frequency marker was identified. In this case only 17 frequency marks are expected and they were all identified in the A/D process except for the one at 10 MHz (some additional tick marks are missing, at 0.5, 1.5, and 8.0 MHz, on this reproduction but are present in the original data). The plasma resonances stimulated by the topside sounder have been identified for this case and are labeled above the ionogram in Figure 5 (top) (see the description in the caption for Figure 5). The Z, O and X ionospheric reflection traces are also labeled in this ionogram.

[13] The false frequency marker in Figure 5 (top) was triggered by the strong narrowband signal near 1.0 MHz caused by the plasma resonances at f_H and f_N. There is also a wideband noise signal between f_N and f_T. The following passive ionogram (Figure 5, bottom) indicated that the former had a component due to natural emissions while the latter did not. It is this combination of active and passive operations of the D mode that enables such labels to be made with confidence.

[14] Figure 6 presents consecutive ISIS 1 ionograms illustrating the G mode and the fringe patterns that appear on the f_H resonance during fixed-frequency operation. These patterns have intrigued scientists for decades; they were recently explained in terms of the beating of two waves, one with $f > f_H$ and one with $f < f_H$, based on a hot plasma dispersion-equation solution when the wave vector makes a small angle to the magnetic field direction [*Muldrew*, 2006].

[15] Figure 7 presents a digital Alouette 2 ionogram. Approximately the first 3 1/2 s were devoted to the frequency flyback from the previous sounder sweep; Alouette 2 did not have fixed-frequency operation. Note, as in the cases of the ISIS 1 and 2 digital ionograms presented in Figures 4–6, the start time refers to the onset of the ionogram frame-sync pulse (see Figure 31 of *Franklin and Maclean* [1969]). Most reproductions of Alouette 2 film ionograms start at the beginning of the frequency sweep near 0.1 MHz, e.g., see Figures 2 and 4 of *Hagg et al.* [1969]. Most of the Alouette 2 data were recorded with the frequency marker data on a separate channel from the sounder-receiver video data. As a result, vertical frequency marker lines are usually not present (as is the case in Figure 7). The frequency sweep rate from 0.1 to 2.0 MHz was less than half that of ISIS 1 or 2 and this slow sweep rate increased the frequency resolution of resonance and cutoff features. The frequency scale in Figure 7 was determined from the frequency values associated with each scan line during the sounder frequency sweep. These frequencies, in turn, were determined by interpolation between the frequency markers detected during the A/D operation. The "0.00" at the left of the frequency scale is not a frequency value but merely indicates that there is no

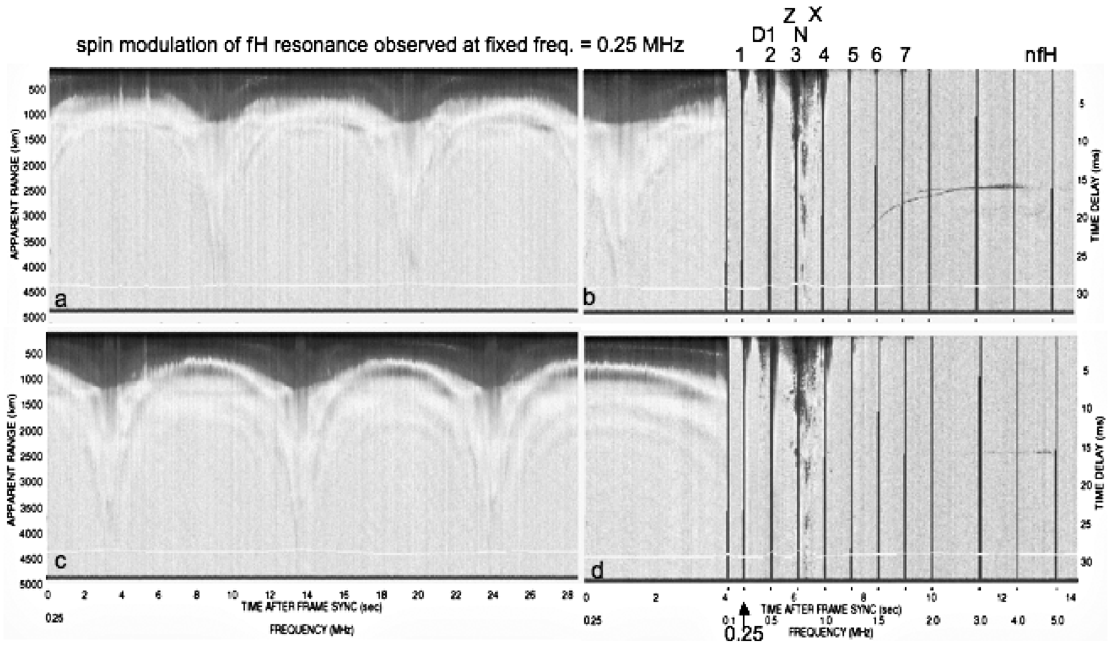

Figure 6. Four consecutive ISIS 1 G-mode ionograms illustrating the effect of satellite spin (period about 20 s) on the sounder-stimulated plasma resonance at $f_H = 0.25$ MHz. The symbols are the same as in Figure 5 with the addition of D1 corresponding to one of the main diffuse resonances (see review by *Benson* [2008]). (b and d) The fixed/swept ionograms have been expanded to resolve plasma resonance features; these ionograms display about 14 s of data whereas (a and c) the fixed-frequency ionograms each display about 28 s of data. (SNT year 1970, day 310, 0330:56–0332:36 UT: for the ionogram in Figure 6c: 2341 GMLTM, −35.8 INVLAT, 2813 km.)

fixed-frequency operation with Alouette 2. See Appendix A and the ISIS project homepage for more details including a discussion of frequency accuracy.

3. Available Analysis Tools and Their Use

[16] An Interactive Data Language (IDL) viewing and analysis program, based on the FORTRAN true-height inversion program of *Jackson* [1969] and available from the ISIS project homepage, allows a user with IDL and FORTRAN to (1) view and scale the Alouette/ISIS digital topside ionograms to produce $N_e(h)$ profiles and orbit-plane contours, (2) view and scale individual sounder-receiver amplitude traces for plasma resonance investigations and for correcting frequency mark and frame-sync identification problems encountered during the A/D operation, and (3) apply different display options, e.g., amplitude thresholding, to assist the interpretation. A description of the inversion of ionospheric reflection traces to $N_e(h)$ profiles using this program was presented by *Benson* [1996], and a description of more recent features of the program is available in the help text with the program and from the ISIS project homepage.

[17] A Topside Ionogram Scaler With True-Height (TOPIST) algorithm was developed to automatically scale the ISIS 2 digital ionograms [*Bilitza et al.*, 2004; *Huang et al.*, 2002]. It automatically reads the digital files, scales the resonances and the reflection traces, and displays the ionogram with the scaled traces and the automatically determined $N_e(h)$ profiles (see Figure 8). The inversion of the echo traces into electron density profiles uses the modified Chebyshev polynomial fitting approach developed by *Huang and Reinisch* [1982]. This automated process has made it possible to scale and invert the large volume of ISIS 2 digitized ionograms. TOPIST has been modified to also be able to scale ISIS 1, and there are plans to modify it so as to also process the Alouette 2 digital topside ionograms.

[18] Both of these programs have been used to produce $N_e(h)$ profiles from the ISIS 2 digital ionograms in Figures 4 and 5 (top) and the results are displayed in Figures 9 and 10, respectively. Figure 9a shows that the hand scaling, based on the inversion program of *Jackson* [1969], and the automatic scaling using TOPIST are in very good agreement for this low-latitude Quito ionogram except near the maximum density of the F layer

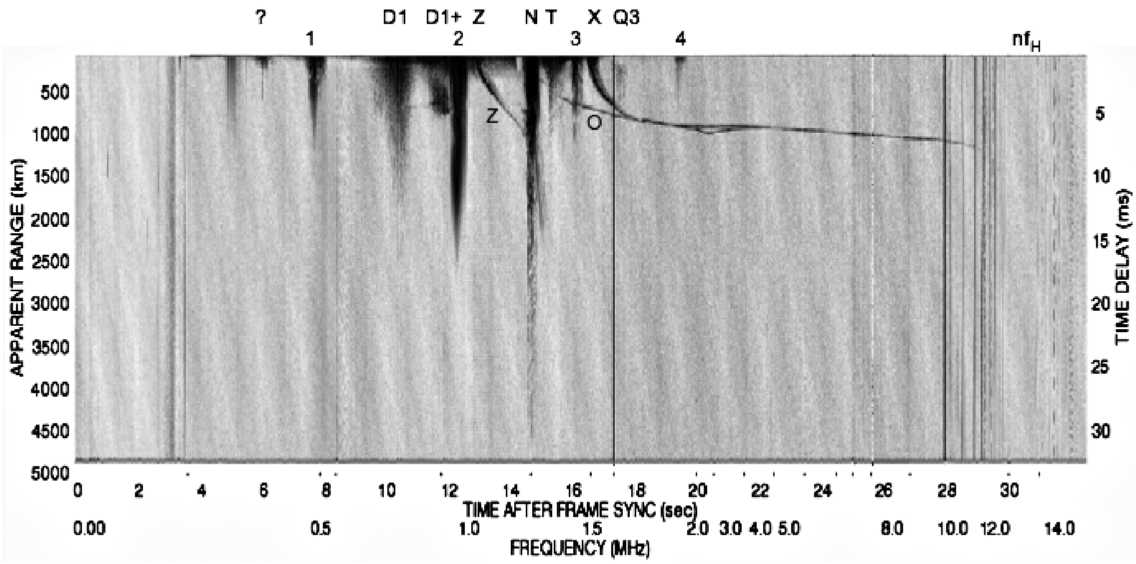

Figure 7. Alouette 2 swept-frequency ionogram illustrating plasma resonances and ionospheric reflection traces. The symbols are the same as in Figures 5 and 6 with the addition of D1+ and Q3 (see review by *Benson* [2008]) and the question mark which may identify a nonlinear product even though it occurs under plasma conditions ($f_T > 2f_H$) where such products are not common [*Benson*, 1982]. The first frequency tick mark (at about 3.7 s after frame sync) approximately corresponds to 0.1 MHz; some of the other marks (including the one at 0.2 MHz) did not reproduce in Figure 7. The 0.00 at the left of the frequency scale indicates that there is no fixed-frequency operation. (SNT year 1966, day 260, 1550:37 UT, 1100 GMLTM, −28.2 INVLAT, 1151 km.)

where TOPIST extrapolates to a lower value for the peak altitude. The TOPIST profile is compared with the predictions of the IRI model in Figure 9b. The IRI profile is observed to be about 24% below the TOPIST profile throughout the topside ionosphere.

[19] Figure 10a compares hand- and TOPIST-scaled profiles for the high-latitude Resolute Bay ionogram of Figure 5 (top). They are seen to be in excellent agreement near the F layer peak altitude, but the hand-scaled profile deviates from the TOPIST profile by an increasing amount with increasing altitude and is about 14% below the TOPIST profile near the altitude of ISIS 2. In this case, hand scaled profiles from the 1970s were available from the NSSDC and they were found to be in excellent agreement with the present hand-scaled values. An inspection of the ionogram of Figure 5 (top) indicated that the scaled value of the electron cyclotron frequency f_H was 0.919 MHz rather than the model value (used by the Jackson inversion program) of 0.917 MHz. In addition to this slight difference (0.2%), however, the values for the resonances and cutoffs indicated that there was a significant gradient in N_e due to the satellite motion during the recording of the ionogram. TOPIST in its auto-scaling mode does not account for this gradient resulting in the differences observed in Figure 10a (TOPIST used f_H = 0.924 MHz as part of the most consistent fit to all of the detected resonances and wave cutoffs). The TOPIST software does allow user intervention (manual scaling) in such cases but the results shown in Figure 10a correspond to the auto-scaling mode. This TOPIST auto-scaled profile is compared with the predictions of the IRI model in Figure 10b. The IRI profile is observed to be about 67% below the TOPIST profile near the altitude of ISIS 2. Efforts are now underway to use results like those shown in Figures 9b and 10b to improve the IRI N_e model in the topside ionosphere. Some of these efforts and their results will be highlighted in the next section.

4. Review of Scientific Results Based on Digital ISIS Topside Ionograms

[20] In a summary of the ISIS program, *Jackson* [1986] indicated that there had been 682 Alouette/ISIS journal publications up to 1 January 1985. *Jackson* [1988b] discussed the scientific accomplishments of the first four of the six spacecraft of the ISIS program. There have been numerous publications since that date based on the ISIS data, including the topside sounder data as

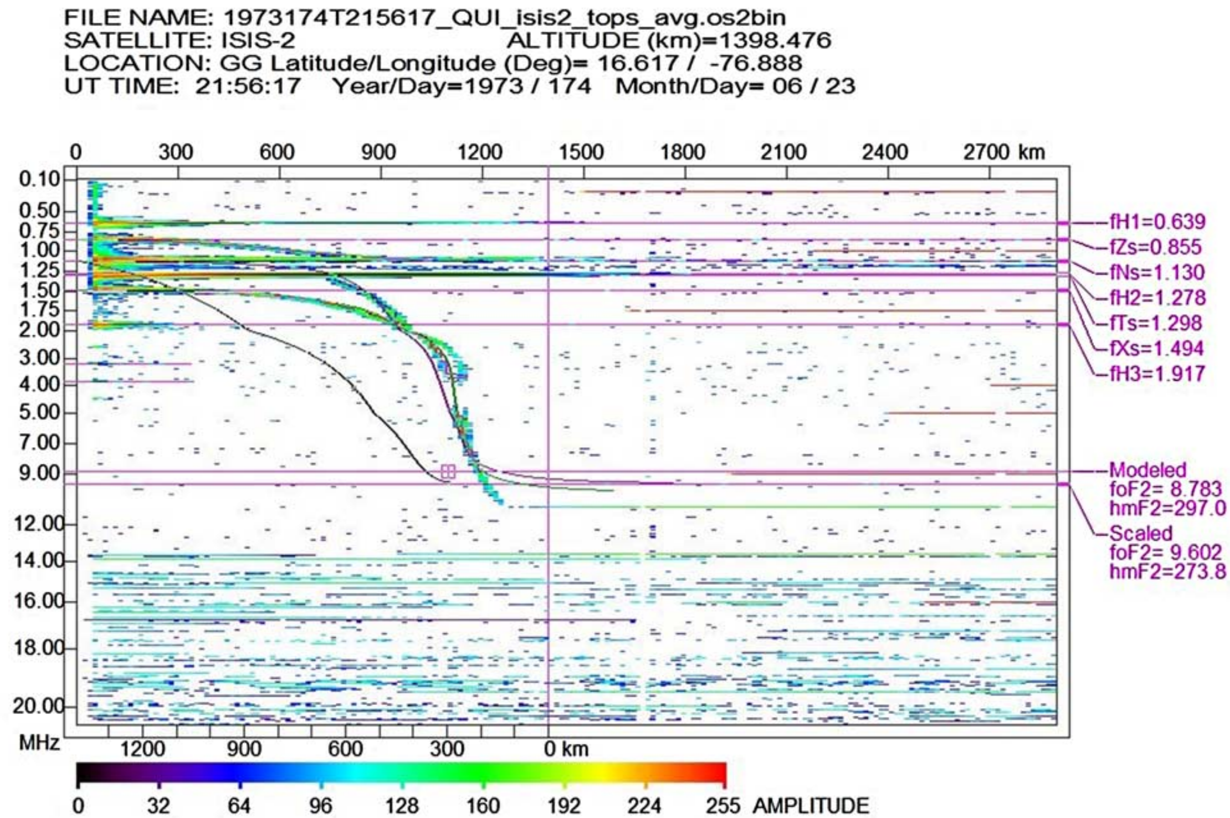

Figure 8. The TOPIST output resulting from the automatic processing of the same ISIS 2 digital ionogram file used to produce Figure 4 (QUI year 1973, day 174, 2156:17). Only the swept-frequency portion is shown. Left scale is the sounder frequency; top scale is the true range from the satellite; bottom scale is the true altitude. The top right quadrant shows the automatically scaled resonance and wave cutoff frequency values corresponding to the satellite location (hence the s in the three-character code); the bottom right quadrant shows the automatically scaled and modeled ionospheric penetration frequency for the ordinary wave foF2 and maximum height of the F layer hmF2. The TOPIST $N_e(h)$ profile calculated from the automatically scaled traces, expressed as a plasma frequency f_N true-altitude profile ($(f_N(\mathrm{kHz})^2 \approx 80.6\ N_e(\mathrm{cm}^{-3}))$), is shown as a heavy black curve. (The apparent kink at 2 MHz is due to a change in the frequency scale.) This profile was then used to calculate the expected ionospheric echo traces and superimpose them as colored O, X, and Z traces on the ionogram to verify the automatic scaling process.

recorded on 35-mm film ionograms. It is not our intent here to review these publications. Rather, our intent is to highlight a number of more recent publications indicating a resurgence of international interest in the ISIS topside sounder data based on the new digital ionograms. These publications have (1) presented evidence of extremely low altitude ionospheric peak densities at high latitudes [*Benson and Grebowsky*, 2001], (2) improved the IRI model for the topside ionosphere [*Bilitza*, 2004, 2009; *Bilitza et al.*, 2006], (3) presented new models for the topside scale height and ion transition height [*Kutiev and Marinov*, 2007; *Kutiev et al.*, 2006; *Marinov et al.*, 2004], (4) investigated transionospheric HF propagation [*James*, 2006], (5) presented convincing new interpretations of the plasma resonance stimulated at f_H (which has challenged theorists for decades) [*Muldrew*, 2006] and of ion emissions stimulated by topside sounders and responsible for proton echoes [*Muldrew*, 1998, 2000], (6) connected magnetospheric N_e profiles to the high-latitude topside ionosphere [*Reinisch et al.*, 2007], and (7) provided a new approach to modeling the F2 peak height hmF2 [*Gulyaeva et al.*, 2008]. In addition, the data have been used in a M.Sc. thesis at the University of Saskatchewan in propagation studies in

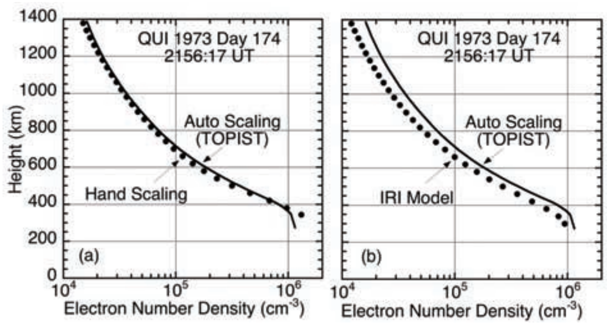

Figure 9. $N_e(h)$ profiles determined from the ISIS 2 digital ionogram in Figure 4. (a) Comparison of hand scaling, based on the inversion program of *Jackson* [1969], and the automatic scaling of Figure 8 using TOPIST [*Bilitza et al.*, 2004; *Huang et al.*, 2002]. (b) Comparison of the TOPIST profile and the profile predicted by IRI-2007 [*Bilitza*, 2001].

preparation for a new satellite mission [*Gillies*, 2006; *Gillies et al.*, 2007], and in a Ph.D. thesis at the University of Massachusetts Lowell leading to publications concerning polar cap N_e distributions [*Nsumei*, 2006; *Nsumei et al.*, 2008a, 2008b].

[21] The digital topside ionograms have been used in review papers that emphasize the application of scientific results obtained from ionospheric topside sounders beyond conventional ionospheric research. (These earlier results were based on the analysis of topside ionograms recorded on 35-mm film.) *Benson and Osherovich* [2004] illustrated the application of the hybrid relationship between some of the sounder-stimulated plasma resonances to the interpretation of similar resonances stimulated in the magnetosphere and to the interpretation of X-ray spectra of disks around neutron stars. *Osherovich et al.* [2005] challenged the plasma physics community to verify a prediction of a new plasma wave mode, involving force-free electromagnetic field cylindrical plasma oscillations associated with field-aligned N_e irregularities, that has been confirmed by Alouette/ISIS topside sounder data. *Benson* [2008] reviewed a number of sounder-stimulated phenomena that required the abandonment of one or more of the common assumptions of a plasma that is cold, homogeneous, neutral, and contains immobile positive ions.

Appendix A: Frequency Determination (and Accuracy) on Alouette and ISIS Digital Ionograms

[22] The following information is based on *Franklin and Maclean* [1969], *Hagg et al.* [1969], *Jackson* [1988a], and experience gained from the A/D conversion of the Alouette and ISIS topside sounder data (see the ISIS homepage at http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html).

[23] As stated in section 2, the frequency information originates from a series of frequency markers either imbedded in the sounder video data (as in the ISIS 1 and 2 and some of the Alouette 2 data) or on a separate data channel on the seven-track analog telemetry tapes (as in most of the Alouette 2 data). In all cases, when a frequency marker was identified during the A/D operation, a flag would be placed on the nearest scan line of the sounder video-amplitude output. This flag consisted of a large amplitude enhancement after the amplitude calibration pulse at the end of the line scan. These amplitude enhancements appear as tick marks below the ionogram image (just above the "Time after frame sync" scales in Figures 4–7). The times of the scan lines associated with frequency markers are included in each digital ionogram file. In the Alouette 2 cases such as in Figure 7, without imbedded frequency markers, the accuracy of the frequency interpolation between frequency markers is limited by these automatically determined scan-line times that best represent the actual frequency marker onset times. In the case of ISIS 1 and 2, and the Alouette 2 digital ionograms containing frequency markers, scaling the actual onset times of the frequency markers can increase this accuracy. This scaling can be accomplished using the line-scan mode of the analysis software available from the ISIS homepage. This software allows a new digital file to be created where the frequency interpolation is based on the hand-scaled frequency marker onset times. This option is only necessary if frequency accuracy greater than that displayed with the digital files is desired. Such increased accuracy is usually only required in investigations of the plasma resonances stimulated by the topside sounders since the frequencies given on the digital ionograms are typically good to within a few percent in the frequency

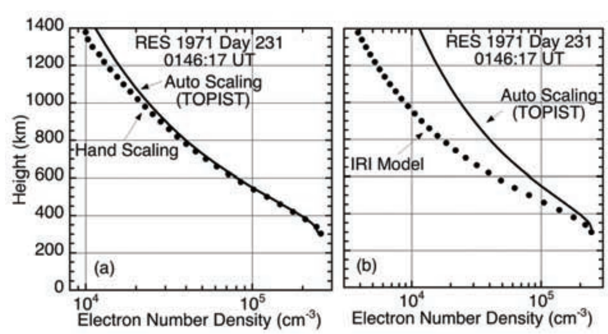

Figure 10. Same as Figure 9 except for the ISIS 2 digital ionogram in Figure 5 (top).

Table A1. Accuracy of the Digital Ionogram Frequency Values

Quantity	Alouette 2	ISIS 1	ISIS 2
PRF (pulses/s)	30	30[a]	45
Sweep rate (MHz)/	≈0.13/ < 2.0/4.3	0.31/0.1–2.0/10.3	0.375/0.1–2.0/8.3
sweep range (MHz)/	≈1.0/ > 2.0/33.3	0.88/2.0–5.0/29.3	1.125/2.0–5.0/25.0
step size (kHz)		1.03/5.0–20.0/34.2	1.5/5.0–20.0/33.3
Maximum	2%/ > 0.2	10.3%/ > 0.1	8.3%/ > 0.1
uncertainty (%)/	0.2%/ < 2.0	0.5%/ < 2.0	0.2%/ < 2.0
near frequency	1.7%/ > 2.0	1.5%/ > 2.0	1.3%/ > 2.0
marker (MHz)	0.3%/ < 13.5	0.6%/ < 5.0	0.5%/ < 5.0
on low (<) or high		0.7%/ > 5.0	0.7%/ > 5.0
(>) frequency side		0.2%/ < 20.0	0.2%/ < 20.0
Maximum uncertainty (%) at f = 0.5 MHz	0.9	2.1	1.7

[a]ISIS 1 had the capability of operating with the PRF = 60 pulses/s, but all of the digital ionograms corresponded to 30 pulses/s.

range containing ionospheric echoes used to derive $N_e(h)$ profiles, as illustrated in Table A1. (Note: even in the low-density Auroral Kilometric Radiation (AKR) source regions, the reflection traces mainly correspond to f > 0.5 MHz [see, e.g., *Benson*, 1981].)

[24] This accuracy is limited by the accuracy of representing the frequency marker onset times used in the frequency interpolation which, in turn, is less than the time interval between sounder scan lines. The values in the column for Alouette 2 indicate that this uncertainty is typically less than 2% in both the expanded frequency range below 2.0 MHz (where the sounder frequency sweep rate is approximately 0.13 MHz/s), and in the frequency range above 2.0 MHz (sweep rate ≈ 1.0 MHz/s). In the former case the uncertainty near the lowest calibrated frequency marker at 0.2 MHz is at most about 2% and near 2.0 MHz it is about 0.2%; in the latter it is at most about 1.7% near 2.0 MHz and 0.3% near the last frequency marker at 13.5 MHz (since the Alouette 2 Pulse Repetition Frequency (PRF) of 30 pulses/s corresponds to a frequency step size between scan lines of 4.3 kHz with sounder frequency f < 2.0 MHz and 33.3 kHz with f > 2.0 MHz).

[25] On the basis of experience gained during the assignment of frequencies to the individual sounder scan lines of an ionogram in the A/D operation with ISIS 2, a different approach was used for ISIS 1 and Alouette 2. In the case of ISIS 2, if a frequency marker was not identified a marker would be inserted based on the expected times of appearance of the markers as determined from a comparison table derived from a hand-scaled ionogram. Since the sounder frequency sweep rate was temperature-dependent, this process sometimes leads to significant errors. Thus it is best to check the header information with the ionogram files, or the separate header files, to determine which, if any, frequency markers were not identified in the A/D operation and were based on substitutions from the table (see the ISIS homepage for details). In addition, no frequency assignments were made if more than the expected number of frequency markers were identified (these extra markers were often the result of interference lines in the frequency range beyond the F2 layer critical frequency fxF2). The result was that some ionograms (with substituted frequency markers) had suspect frequencies and many, with good data in the frequency region of interest, i.e., f < fxF2 but with too many detected frequency markers, did not contain useable frequency information (all sounder scan lines were assigned a default frequency value of −1.0E+31).

[26] To overcome these limitations experienced with the ISIS 2 digital ionograms, the frequency assignment procedure for ISIS 1 and Alouette 2 was based on comparing the time differences between the observed frequency markers and those in the reference table starting with the lowest two frequency markers and stepping through the frequency markers as the frequency (and sweep time) increases. This process continues through all of the frequency markers until the highest marker is reached or until a discrepancy is encountered between the observed and expected time difference between markers (again, see the ISIS homepage for details). Once such a discrepancy was encountered, frequency interpolation is performed between the frequency markers up to the last good frequency marker to assign frequency values for the individual scan lines up to this marker; the frequency values for the scan lines at higher frequencies are assigned a default frequency value of −1.0E+31. Since the last good frequency marker is usually at f > fxF2, this procedure resulted in more ionograms with useable frequency values than was the case with the ISIS 2 processing.

[27] There is an additional complication in the case of the frequency interpolation procedure used on ISIS 1 digital ionograms. There is a significant nonlinearity in the frequency sweep rate in the frequency range between the 2.0 and 3.0 MHz frequency markers and a lesser nonlinearity between the 5.0 and 6.0 MHz markers.

Table A2. Corrections for the Nonlinearities in the ISIS 1 Frequency Sweep Rate[a]

f_A (MHz)	f_R (MHz)
2.00	2.00
2.165	2.10
2.39	2.30
2.75	2.70
3.00	3.00
5.00	5.00
5.52	5.50
6.00	6.00

[a]From 2 to 3 and 5 to 6 MHz where f_A represents the apparent frequency (as scaled using linear interpolation between the frequency markers) and f_R represents the real frequency.

Curves to correct for these nonlinearities were produced at the CRC in Ottawa shortly after the launch of ISIS 1 (J. E. Jackson, Minutes of the Twenty-First Meeting of the ISIS Working Group, Communications Research Centre, Ottawa, Ontario, Canada, 19–20 May 1970). Such curves were used during the manual scaling of the analog ionograms from 35-mm film in order to arrive at the correct, or true, frequencies. The analysis program available from the ISIS homepage, based on the true-height inversion method of *Jackson* [1969], assumes such linear interpolations were employed in scaling the ionospheric reflection traces. This program approximates the CRC correction curves by linearly interpolating between the values given in Table A2.

[28] A linear interpolation was used between the 2 and 3 and the 5 and 6 MHz frequency markers during the creation of the digital ISIS 1 ionograms so that optimal $N_e(h)$ profiles would result when these digital files were processed using the analysis program, based on the Jackson inversion method, available from the ISIS homepage (see this page for more details). For analysis of ISIS 1 digital ionograms for purposes other than obtaining $N_e(h)$ profiles, e.g., the inspection of plasma resonances, corrections based on Table A2 should be applied.

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References

Benson, R. F. (1972), Ionospheric plasma resonances: Time durations vs. latitude, altitude, and fN/fH, *Planet. Space Sci.*, *20*, 683–706.

Benson, R. F. (1981), Auroral kilometric radiation source region observations from ISIS 1, in *Physics of Auroral Arc Formation*, *Geophys. Monogr. Ser*, vol. 25, edited by S.-I. Akasofu and J. R. Kan, pp. 369–379, AGU, Washington, D. C.

Benson, R. F. (1982), Stimulated plasma instability and nonlinear phenomena in the ionosphere, *Radio Sci.*, *17*, 1637–1659.

Benson, R. F. (1996), Ionospheric investigations using digital Alouette/ISIS topside ionograms, in *Proceedings of 1996 Ionospheric Effects Symposium*, edited by J. M. Goodman, pp. 202–209, Technol. for Commun. Int./BR Commun., Alexandria, Va.

Benson, R. F. (2008), Plasma physics using space-borne radio sounding, in *CP974, Radio Sounding and Plasma Physics*, edited by P. Song et al., pp. 20–33, Am. Inst. of Phys., Lowell, Mass.

Benson, R. F., and J. M. Grebowsky (2001), Extremely low ionospheric peak altitudes in the polar hole region, *Radio Sci.*, *36*, 277–285.

Benson, R. F., and V. A. Osherovich (2004), Application of ionospheric topside-sounding results to magnetospheric physics and astrophysics, *Radio Sci.*, *39*, RS1S28, doi:10.1029/2002RS002834.

Bilitza, D. (2001), International reference ionosphere 2000, *Radio Sci.*, *36*(2), 261–275.

Bilitza, D. (2004), A correction for the IRI topside electron density model based on Alouette/ISIS topside sounder data, *Adv. Space Res.*, *33*, 838–843.

Bilitza, D. (2009), Evaluation of the IRI-2007 model options for the topside electron density, *Adv. Space Res.*, in press.

Bilitza, D., X. Huang, B. W. Reinisch, R. F. Benson, H. K. Hills, and W. B. Schar (2004), Topside ionogram scaler with true height algorithm (TOPIST): Automated processing of ISIS topside ionograms, *Radio Sci.*, *39*, RS1S27, doi:10.1029/2002RS002840.

Bilitza, D., B. W. Reinisch, S. M. Radicella, S. Pulinets, T. Gulyaeva, and L. Triskova (2006), Improvements of the International Reference Ionosphere model for the topside electron density profile, *Radio Sci.*, *41*, RS5S15, doi:10.1029/2005RS003370.

Daniels, F. (1971), ISIS-II spacecraft, *CRC Rep. 1218*, 81 pp., Commun. Res. Cent., Ottawa, Ont., Canada.

Donley, J. L., L. H. Brace, J. A. Findlay, J. H. Hoffman, and G. L. Wrenn (1969), Comparison of results of Explorer XXXI direct measurement probes, *Proc. IEEE*, *57*, 1078–1084.

Florida, C. D. (1969), The development of a series of ionospheric satellites, *Proc. IEEE*, *59*, 867–875.

Franklin, C. A., and M. A. Maclean (1969), The design of swept-frequency topside sounders, *Proc. IEEE*, *57*, 897–929.

Gillies, R. G. (2006), Modelling of transionospheric HF radio wave propagation for the ISIS II and ePOP satellites, M.Sc. thesis, Inst. of Space and Atmos. Stud., Univ. of Saskatchewan, Saskatoon, Canada. (Available at http://library2.usask.ca/theses/available/etd-02062006-092832/unrestricted/thesis.pdf)

Gillies, R. G., G. C. Hussey, H. G. James, G. J. Sofko, and D. André (2007), Transionospheric modelling results for ISIS II in preparation for ePOP, *Ann. Geophys.*, *25*, 87–98.

Gulyaeva, T. L., P. A. Bradley, I. Stanislawska, and G. Juchnikowski (2008), Towards a new reference model of hmF2 for IRI, *Adv. Space Res.*, *42*, 666–672, doi:10.1016/j.asr.2008.02.021.

Hagg, E. L., E. J. Hewens, and G. L. Nelms (1969), The interpretation of topside sounder ionograms, *Proc. IEEE*, *57*, 949–960.

Huang, X., and B. W. Reinisch (1982), Automatic calculation of electron density profiles from digital ionograms: 2. True height inversion of topside ionograms with the profile-fitting method, *Radio Sci.*, *17*, 837–844.

Huang, X., B. W. Reinisch, D. Bilitza, and R. F. Benson (2002), Electron density profiles of the topside ionosphere, *Ann. Geophys.*, *45*, 125–130.

Jackson, J. E. (1969), The reduction of topside ionograms to electron-density profiles, *Proc. IEEE*, *57*, 960–976.

Jackson, J. E. (1986), Alouette-ISIS program summary, *NSSDC Rep. 86–09*, Natl. Space Sci. Data Cent., Greenbelt, Md.

Jackson, J. E. (1988a), Data users' note: Calibrations and identification of Alouette and ISIS topside ionograms, *NSSDC Rep. 88–06*, Natl. Space Sci. Data Cent., Greenbelt, Md.

Jackson, J. E. (1988b), Results from Alouette 1, Explorer 20, Alouette 2 and Explorer 31, *NSSDC Rep. 88–10*, Natl. Space Sci. Data Cent., Greenbelt, Md.

James, H. G. (2006), Effects on transionospheric HF propagation observed by ISIS at middle and auroral latitudes, *Adv. Space Res.*, *38*, 2303–2312, doi:10.1016/j.asr.2005.2303.2114.

Kutiev, I., and P. Marinov (2007), Topside sounder model of scale height and transition height characteristics of the ionosphere, *Adv. Space Res.*, *39*, 759–766.

Kutiev, I., P. Marinov, and S. Watanabe (2006), Model of topside ionosphere scale height based on topside sounder data, *Adv. Space Res.*, *37*, 943–950.

Marinov, P., I. Kutiev, and S. Watanabe (2004), Empirical model of O+-H+ transition height based on topside sounder data, *Adv. Space Res.*, *34*, 2021–2025.

Muldrew, D. B. (1998), Topside-sounder proton-cyclotron echo generation from a plasma memory process and electron Bernstein-wave propagation, *Radio Sci.*, *33*, 1395–1411.

Muldrew, D. B. (2000), Correction to "Topside-sounder proton-cyclotron echo generation from a plasma memory process and electron Bernstein-wave propagation" by D. B. Muldrew, *Radio Sci.*, *35*, 1047–1048.

Muldrew, D. B. (2006), The Poynting vector applied to the complex refractive index in a hot plasma near the electron-cyclotron frequency, and to the cyclotron resonance observed on topside ionograms, *Radio Sci.*, *41*, RS6006, doi:10.1029/2006RS003496.

Nsumei, P. A. (2006), On the polar cap plasma properties and processes: Electron density distribution, flow, and driving forces, Ph.D. thesis, Univ. of Mass., Lowell.

Nsumei, P. A., B. W. Reinisch, P. Song, J. Tu, and X. Huang (2008a), Polar cap electron density distribution from IMAGE radio plasma imager measurements: Empirical model with the effects of solar illumination and geomagnetic activity, *J. Geophys. Res.*, *113*, A01217, doi:10.1029/2007JA012566.

Nsumei, P. A., P. Song, B. W. Reinisch, J. Tu, and X. Huang (2008b), Ionospheric electron upflow in the polar cap region: Derived from ISIS 2 measurements, *J. Geophys. Res.*, *113*, A03312, doi:10.1029/2007JA012567.

Osherovich, V. A., R. F. Benson, and J. Fainberg (2005), Electromagnetic bounded states and challenges of plasma spectroscopy, *IEEE Trans. Plasma Sci.*, *33*, 599–608.

Pulinets, S. A., and R. F. Benson (1999), Radio-frequency sounders in space, in *Review of Radio Science 1996–1999*, edited by W. R. Stone, pp. 711–733, Oxford Univ. Press, Oxford, U. K.

Reinisch, B. W., P. Nsumei, X. Huang, and D. K. Bilitza (2007), Modeling the F2 topside and plasmasphere for IRI using IMAGE/RPI, and ISIS data, *Adv. Space Res.*, *39*, doi:10.1016/j.asr.2006.1005.1032.

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